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A Comparison of Intercontinental Clock Synchronization by VLBI and the NTS Satellite

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The intercontinental clock synchronization capabilities of Very Long Baseline Interferometry (VLBI) and the Navigation Technology Satellite (NTS) have been compared at the NASA Deep Space Net complexes at Madrid, Spain and Goldstone, California. The VLBI experiments used the Wideband VLBI Data Acquisition System developed at the NASA Jet Propulsion Laboratory. The Naval Research Laboratory NTS Satellites were used with NTS Time Transfer Receivers developed by the Goddard Space Flight Center. The two methods agreed to within about 0.5 μs.

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A COMPARISON OF INTERCONTINENTAL CLOCK SYNCHRONIZATION
BY VLBI AND THE NTS SATELLITE

INTRODUCTION

A series of experiments were conducted to compare the intercontinental clock synchronization capabilities of the Navigation Technology Satellite (NTS) system and a Very Long Baseline Interferometry (VLBI) system in use in the NASA Deep Space Net. These measurements agreed to within 0.5 μs.

The experiments were conducted between the 64 m Deep Space Stations at Goldstone, California (DSS 14) and Madrid, Spain (DSS 63). The VLBI experiments used the Wideband Digital VLBI Data Acquisition System (WBDAS) that was developed at the NASA Jet Propulsion Laboratory. This system has been in routine use in its present configuration since January 1978. The satellite time transfer experiments used the NTS-1 satellite, designed and built by the Naval Research Laboratory, and the NTS time transfer receivers (NTS/TTR) developed by the Goddard Space Flight Center. The NTS receivers were brought to the Deep Space Stations for these experiments.

EXPERIMENT CONFIGURATION

The configuration of the VLBI data acquisition system and the NTS time transfer receiver at each DSS is shown in Fig. 1. Of particular interest is the clock system. The primary frequency standard at each station was an HP5061A-004 Cesium oscillator. For the purpose of this experiment, the station reference point is the 1 pps signal, since both the VLBI and the NTS systems connect to the station timing system at this point. In comparing the results for the two systems the cable delays were accounted for according to the specified or measured physical lengths of the cables, and the delay from the 1 pps input to the 1 pps output of the NTS receivers was measured. The delay within the Wide Band Data Acquisition System units is less than 20 ns and was not significant in this experiment.

NTS TIME TRANSFER RESULTS

Time transfer using an NTS satellite is accomplished by using the oscillator on the satellite as a portable clock, and reading this clock over a microwave link as the satellite passes near the ground stations.

The major source of error in the time transfer technique is the uncertainty in the position of the spacecraft. This is reflected as uncertainties in the stability of the oscillator on the satellite and propagation delays in the ionosphere.
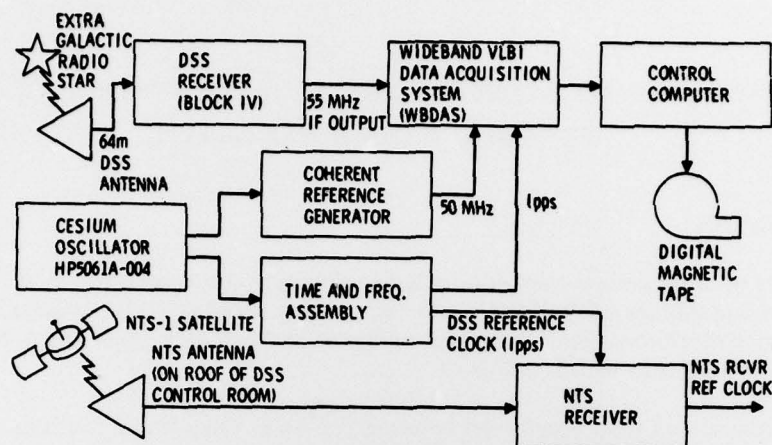
Fig. 1 — Configuration of the NTS Time Transfer Receiver and the
VLBI System in a DSS

Raymond et al., [1] describes the timing receiver used here, and presents the results of some time transfer experiments between Rosman, North Carolina and the U.S. Naval Observatory using the NTS-1 satellite. These experiments demonstrated rms errors of 86 ns with respect to a portable clock. Errors over intercontinental distances are somewhat more, due to time separation, orbit errors, and larger ionospheric effects. The ionospheric effect and its uncertainty is often on the order of 1 μs at the radio frequency of 335 MHz, but this error source tends to cancel when the time and space separations are small.

The NTS time transfer measurements reported here were adjunct to the six nation cooperative experiment described by Buisson et al., [2]. The receiver used at the Madrid station was the same as the one used at Bureau International de l'Heure, Paris, France, and a spare receiver was used at Goldstone, California. As indicated in Fig. 1, the receivers were installed in the DSS control rooms, with the NTS/TTR antennas on the roofs. The positions of the antennas were measured to within a meter with respect to benchmarks at the stations, and errors in the antenna coordinates are not expected to contribute significantly to errors in the results. The data were processed such that the results gave the offsets in the DSS clocks with respect to the USNP master clock C8D at the Naval Observatory.

Figure 2 shows the results of thirteen measurements made at Goldstone from day 145 (May 25) through day 151 (May 31) of 1978. The results are corrected for a delay of 0.232 μs from the Goldstone clock reference point to the NTS receiver clock. A least squares linear fit to the data results in an offset USNO minus Goldstone of -0.688 μs at 0 hours on day 147, with a rate offset of -0.9×10^{-12} and an rms residual of 0.341 μs.

Ten measurements were conducted at Madrid during the same time frame, and the results are shown in Fig. 3. These results are corrected for a delay of 0.279 μs from the DSS clock reference point to the NTS receiver output. The least squares fit indicates an offset USNO minus Madrid of 8.593 μs at 0 hours on day 147, with a rate offset of -0.28×10^{-12} and rms residuals of 0.226 μs.
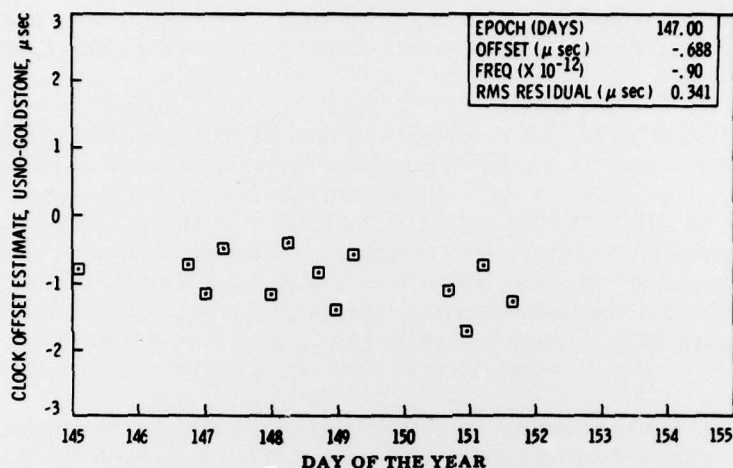
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Fig. 2 — NTS-1 time transfer results for Goldstone
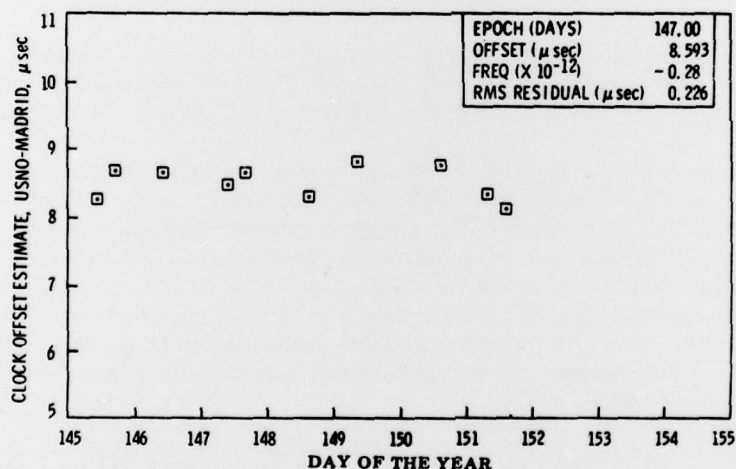USNOMC(C8D) — Goldstone (DSS 14)

Fig. 3 — NTS-1 time transfer results for Madrid
USNOMC(C8D) — Madrid (DSS 63)

VLBI SYSTEM DESCRIPTION

Station clock offset is one of the many parameters that can be estimated by Very Long Baseline Interferometry. The random radio signal from an extragalactic radio star is observed at two antenna stations. Because the antennas are widely separated and the Earth is rotating, there is a time varying time delay between the arrival of the signal at the two stations. This time delay and its derivative can be estimated from the geometry, and can be

measured by cross-correlating the signals received at the two stations. Because the arrival of the signal is time-tagged by the clocks at the stations, the difference between the measured and the predicted time delays forms an estimate of the offset between the station clocks.

The Wideband VLBI Data Acquisition System (WBDAS) has been described elsewhere [3], so we present only a brief description here. A simplified block diagram of the WBDAS is given in Fig. 4. As shown in Fig. 1, the system interfaces to the standard DSS receiving system at the 55 MHz ± 18 MHz output of the Block IV receiver. The receiver output is digitally demodulated to baseband by sampling at 50 MHz in each of two phase-quadrature 3-bit analog-to-digital converters. The A/D converter outputs are then low pass filtered, if desired, by summing N consecutive samples in a digital integrate-and-dump filter. These experiments used both unfiltered sampling, and filtering with N = 3, for a filter bandwidth of 16 2/3 MHz, which was a reasonably good match to the receiver system bandwidths.

The digital filter outputs are quantized to one bit and stored in a high-speed buffer of 4096 bits. When the buffer is full, which takes about 120 μs for N = 3, sampling is inhibited and the buffer is emptied through the control computer onto digital magnetic tape. The total data rate onto magnetic tape is 57 kb/s, consisting of 14 bursts of 4096 bits. The control computer utilizes knowledge of the radio source position to predict the geometric signal delay from the source, and controls the hardware buffer so that the same segments of the signal wavefront are sampled and recorded at both stations.

The utilized receiver bandwidth of 16 2/3 MHz is sufficient to achieve measurement resolutions of under 10 ns for any radio source which is strong enough to be detected. Resolution of about 1 ns is achieved with strong sources, using 1 min of data (3×10^6 bits).

The accuracy of the system is limited primarily by propagation uncertainty in the ionosphere, which is often 20 ns at the S-band receiving frequency of 2290 MHz; by uncertainty in the Earth's orientation (UTI), which causes errors of about 5 ns; by errors in the positions of the radio sources; and by receiving system delays. We currently estimate the total day to day consistency in results to be about 30 ns; and the constant bias due to unknown but constant receiving system delays to be another 40 ns, for an estimated root sum squared total error of 50 ns. (It is possible that the error in the receiving system delays is greater than 40 ns, because the delays have not been measured, but were estimated from cable length specifications.)

VLBI RESULTS AND COMPARISON TO NTS RESULTS

Four VLBI clock sync experiments were conducted on May 15, 20, 24, and 27, 1978. The last three experiments consisted of from 8 to 13 total observations of 7 to 11 radio sources over total time spans of 1.5 to 3 h. On May 15, due to operational problems, only two sources were observed, about 10 min apart. Despite the discrepancy in the amount of data, the expected clock sync errors are about the same on all days, except that the expected error on May 15 is slightly larger. As shown in Fig. 4, the computer associated with the WBDAS is interfaced to data transmission lines. We used this capability to transmit some of the data from Madrid to JPL, and we processed this data between experiments to provide confirmation that the stations were properly configured.
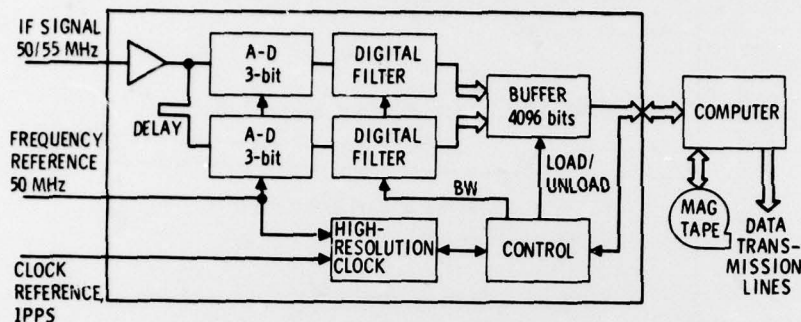
Fig. 4 — Wideband Digital Data Acquisition System block diagram

Figure 5 shows the final clock offset estimates for the four days. The results are compensated for all known clock and signal delays and are expressed as Goldstone clock minus Madrid clock. A linear least squares fit to the data yields an estimated clock offset of 8.775 μs at 0 hours on day 147, with a rate offset of 0.33×10^{-12}. The rms of the residuals is 20.7 ns, and the sample standard deviation is 29.3 ns, with the difference due to estimating two parameters with only four data points. This is compatible with our a priori estimate of day-to-day consistency of 30 ns.

Also shown in Fig. 5 is the NTS time transfer experiment estimate of the clock and clock rate offset between the two stations. This estimate is 9.281 μs at 0 hours on day 147, with a rate offset of 0.62×10^{-12} which is just the USNO-Madrid result of Fig. 3, minus the USNO-Goldstone result of Fig. 4. The difference between the VLBI and the NTS estimates is 0.506 μs at 0 hours on day 147, with a rate offset of 0.29×10^{-12}. Day 147 was chosen as the reference epoch because both experiments were in progress at that time.

The difference of 0.506 μs between the two experiments is probably due to the ionospheric effects on the NTS measurements, both directly and through errors in orbit determination. There may also be a larger constant error in the estimated station delays for the VLBI experiment than the anticipated ± 40 ns. The difference between the rate estimate is within the error bounds of the NTS experiment.

OSCILLATOR STABILITY ESTIMATE FROM THE VLBI DATA

The instabilities of the HP5061A-004 Cesium oscillators at the two stations can be bounded by using the VLBI results. The four experiments form three time intervals of 3 to 4.5 days. Differencing the clock offset estimates for successive experiments leads to frequency offset estimates of 1.85×10^{-13}, 4.26×10^{-13}, and 3.63×10^{-13}. Successive absolute differences between the offsets, divided by root 2, yield Allan variance σ's of 1.70×10^{-13} and 0.44×10^{-13}. The average of the two Allan variance pairs yields an average σ of 1.24×10^{-13} with a sample sigma of 1.16×10^{-13}.

We have estimated the combined instability of the two Cesium oscillators, the station time distribution systems, and the VLBI measurements, over 3 to 4 day intervals to be
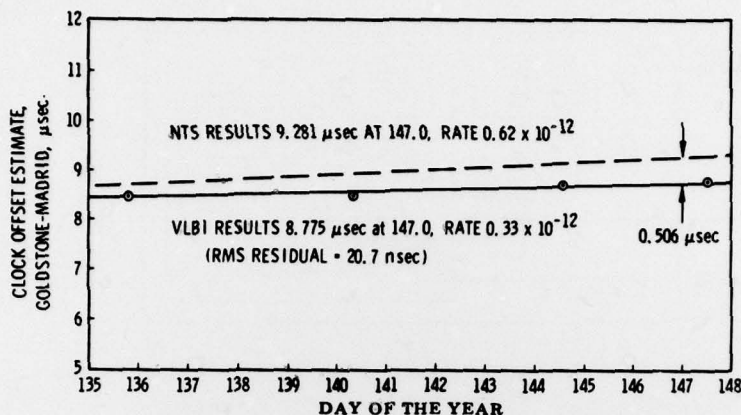
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Fig. 5 — VLBI clock offset measurements, and comparison to NTS results, Goldstone (DSS 14) — Madrid (DSS 63)

approximately one part in 10^{13} with an uncertainty of one part in 10^{13}. By increasing the time interval to about 10 days and by reducing the ionospheric effect on the VLBI measurements by use of X-band, an order of magnitude improvement in measurements seems feasible.

CONCLUSION

By intercomparison of results, we have demonstrated the absolute accuracy of the NTS time transfer system and the WBDAS VLBI system to be 0.5 μs or better between Goldstone, California, and Madrid, Spain. For the VLBI system, we have produced clock sync residuals that demonstrate day to day consistency at the 20-30 ns level, and the ability to use this system to measure long term frequency stability at the 10^{-13} level.

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